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Precipitation Forecast Sensitivity to GPS Precipitable Water Observations Combined with GOES Using RUC-2

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1. INTRODUCTION

For lack of sufficient observations, definition of atmospheric moisture fields (water vapor and cloud) remains a difficult problem whose solution is essential for improvement of weather forecasts. In the past few years, a largely unanticipated technology for estimating atmospheric water vapor has emerged in which the total vapor in a vertical column is estimated by measuring signal delays of GPS (Global Positioning System) signals (Bevis et al. 1994, Askne and Nordius 1987). This delay results in a small error in the estimated position of the receiver known as the zenith wet delay (ZWD), which is nearly proportional to the vertically integrated water vapor, or integrated precipitable water (IPW). NOAA's Environmental Research Laboratories (ERL) are now producing these estimates (i.e., vertically integrated water vapor) for 15 GPS sites in the United States, with an additional 18 sites expected later in 1997.

These GPS-IPW observations provide high-frequency, accurate observations unaffected by weather conditions, as shown by tests done by ERL and others. Satellite-based IPW estimates are also available, but have limitations. Those based on measurements of upwelling infrared radiation are reliable only in cloud-free areas. Those based on upwelling microwave radiation (available only over the oceans) are valid in cloudy regions but are less accurate than the IR-based estimates. The GPS-based IPW measurements are most valuable when satellites cannot obtain good measurements, mainly in cloudy regions where, from a forecasting perspective, the need to have accurate measurements is highest.

Using the new version of the Rapid Update Cycle (RUC-2, Benjamin 1998), various tests are being performed to examine the accuracy of IPW information and the impact of GPS-IPW observations on short-range forecasts of moisture and precipitation. In order to gain a good assessment of the impact of new observation systems, it is critical to determine the incremental value of the new system in the presence of other, already available observations. Since GOES precipitable water data, rawinsonde, and hourly surface moisture data are already being assimilated into the experimental RUC-2, it is well-suited for such an investigation.

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2. CURRENT AND FUTURE GPS-IPW NETWORKS

Figure 1. NOAA/ERL GPS-IPW network as of October 1997.

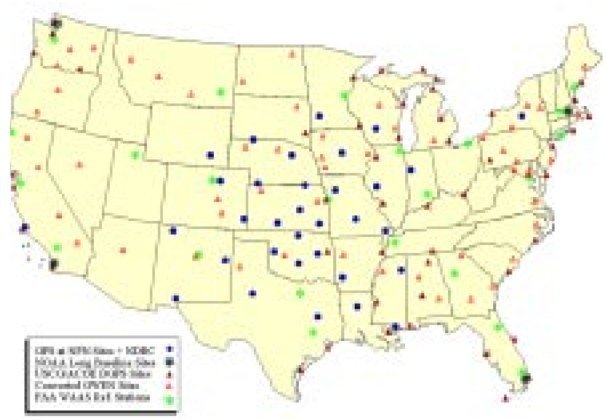

Figure 2. Potential GPS-IPW network in 3-5 years.

As of mid-October 1997, 15 GPS-IPW systems are operating at NOAA Profiler Network sites in the Continental U.S. and Alaska. Fig. 1 is a map of the U.S. and Alaska showing the current configuration of the NOAA/ERL GPS-IPW network and its expected near-term expansion. Of special importance are the U.S. Coast Guard Differential GPS (DGPS) sites, located mostly along the Gulf of Mexico, that will provide additional water vapor observations in this relatively data poor region. The inclusion of USCG DGPS sites into the NOAA GPS-IPW network also demonstrates the feasibility of using the growing number of GPS systems installed, operated, and maintained by other federal agencies, especially the U.S. Department of Transportation, to expand the number of GPS-IPW sites available to NOAA at very low cost and risk.

The potential for expansion of the GPS-IPW network in the next 3-5 years is considerable, as depicted in Fig. 2. The GPS sites capable of being integrated into this network include all of the NOAA Profiler Network (NPN) sites, USCG DGPS sites, converted Ground Wave Emergency Network (GWEN) sites to be operated by the Department of Transportation, and FAA Wide Area Augmentation System (WAAS) control stations. Options for still further expansion of the GPS-IPW network include utilization of GPS sites of opportunity that may be operated by universities and private companies, and installation of GPS receivers at NWS WFOs and ASOS sites.

Table 1: 3h RUC vs. GPS-IPW, 5-15 Mar 97

Site	Mean difference (mm)	Standard dev. diff. (mm)
PLTC	-0.1	1.7
HBRK	0.2	1.9
HVLK	-0.3	1.9
NDSK	-0.7	2.0
VCIO	0.2	2.2
LMNO	0.7	2.3
HKLO	0.5	2.4
GDAC	0.3	2.4
PRCO	0.3	2.6
DQUA	-0.7	2.7
WSMN	1.2	2.9
NDBC	1.7	4.8

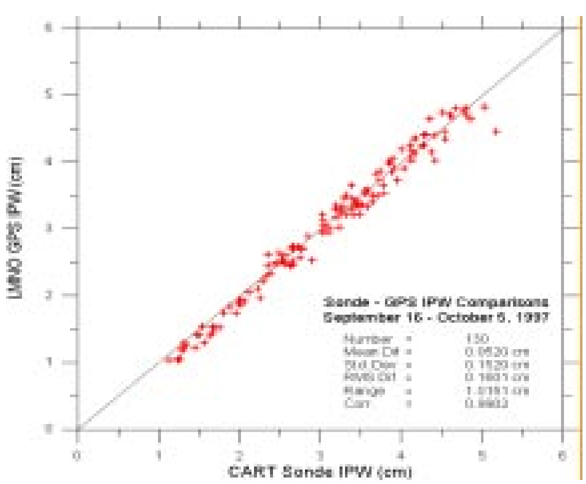

Figure 3. Scatter plot of GPS and rawinsonde observations of integrated precipitable water at the ARM-CART central facility

3. THE ACCURACY REQUIREMENT FOR GPS PRECIPITABLE WATER

Despite the fact that there are no real-time moisture observations available in cloudy conditions other than rawinsondes (12 h frequency) and surface observations, the skill of short-range precipitable water forecasts over the United States is reasonably good, especially away from coastal areas. Table 1 shows differences between GPS-IPW observations (using “rapid orbits” - see Wolfe et al. 1998) and 3-h analyses from an experimental version of RUC-2. The standard deviation difference is below 3 mm at all sites except for NDBC, on the Gulf Coast. In order, for GPS-IPW observations to add information to what is already known, this suggests that, away from U.S. coasts, GPS-IPW should have an accuracy of < 2 mm and closer to 1 mm, if possible.

Fortunately, using improved (non-predicted) GPS satellite orbit data, such accuracy is possible. Fig. 3 shows a scatter plot of sonde IPW vs. GPS IPW during the Atmospheric Radiation Measurement (ARM) water vapor IOP held in September - October, 1997. The GPS-IPW observing system was located at the Lamont NOAA Profiler site, 9 km north of the ARM Cloud and Radiation Testbed (CART) central facility where all balloon launches took place. An average of 6 Vaisala sonde launches per day were made. The standard deviation between these two observation systems was about 1.5 mm, which includes measurement for both systems as well as small-scale variability.

4. ASSIMILATION OF INTEGRATED PRECIPITABLE WATER DATA

The analysis method currently used in RUC-2 is a multivariate optimal interpolation (OI) which accounts for the expected errors of both the observations and forecast background and weights the final result accordingly. In the near future, a 3-d variational analysis (Devenyi and Benjamin 1998) will be substituted for the OI analysis in the RUC-2. The steps in including the GPS (and other) PW data directly into the RUC-2 OI scheme are shown below:

1) Access integrated PW field for the forecast background (already calculated).

2) Calculate PW residuals (difference between obs and background) at each PW observation location. Only use GOES PW where p_{sfc} > 950 hPa to ensure that observation retrieval used p_{sfc} close to that of model.

3) Perform a two-pass univariate OI analysis of the PW increment (correction to background) field, using observational errors of 0.1 mm for GPS PW (non-real-time) and larger value for GOES PW. The two passes use approximate e-folding correlation distances of 140 km and 67 km, respectively, to allow both medium- and fine-scale structure. This results in a PW increment field, from which a percentage change can be calculated at each grid point.

4) Distribute the PW increment calculated in step 3 according to the background forecast profile of water vapor. The absolute moisture at each level will be either increased or

decreased by an equal percentage (at a given grid point), but the shape of the moisture profile will remain unchanged.

5) If, after step 4, any supersaturation occurs at any individual levels, adjust vertical distribution in the column so that correct increase of PW is still achieved but without supersaturation.

6) Continue with rest of analysis, including that of single-level moisture observations. Thus, the non-integrated moisture observations are given the “final say” in the moisture analysis.

This analysis procedure follows the general proposal of Gal-Chen et al. (1986) for assimilating vertically integrated quantities that the background vertical structure be retained in that assimilation. Several studies have been made concerning the assimilation of satellite-derived PW data. In some of these studies (Aune 1994, Ledvina and Pfaendtner 1995), the model background is adjusted to an analysis of the PW observations. However, the adjustment proposed above is to an analysis of the PW residuals to give a more accurate moisture analysis between PW observations. Filiberti (1994) showed successful experiments for assimilating SSM/I PW values with an analysis technique equivalent to that proposed here using the French PERIDOT forecast model.

5. RESULTS FROM AN INITIAL GPS-IPW DATA SENSITIVITY EXPERIMENT

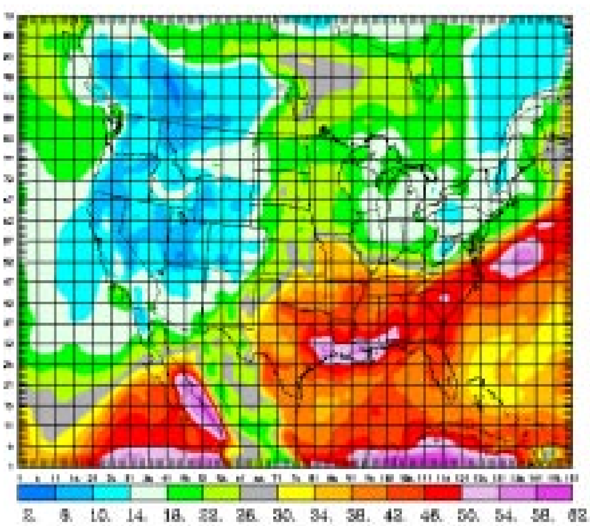

Figure 4. Initial precipitable water field (mm) at 1200 UTC 27 June 1997. RUC-2 analysis using GPS and GOES IPW observations.

To adequately assess the impact of GPS-IPW observations, a pair of parallel cycles of the RUC/MAPS assimilation system with and without GPS-IPW will soon begin. The results from that experiment will be reported at the conference. Here we show results from a single preliminary experiment from 27 June 1997 performed with the 40-km RUC-2 (Benjamin et al. 1998).

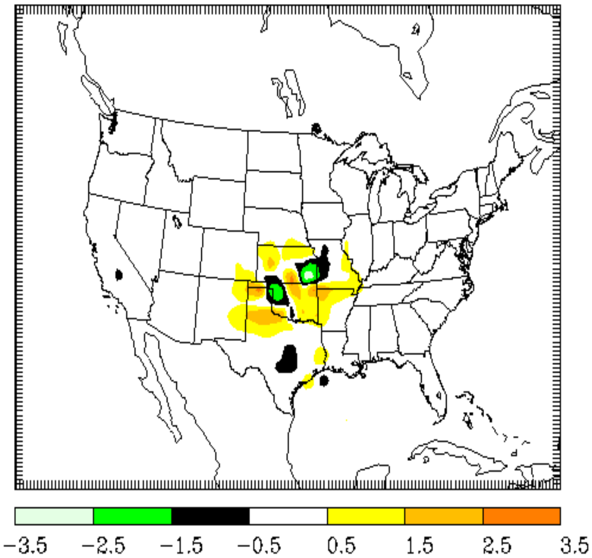

Figure 5. Change in precipitable water analysis (mm) from inclusion of GPS-IPW data. At 1200 UTC 27 June 1997.

For this case, 12-h forecasts were run with and without GPS-IPW observations. The analysis background at the initial time of 1200 UTC was a 6-h forecast initialized at 0600 UTC. Both analyses used all other available data, including GOES-derived products of precipitable water, and surface and rawinsonde *in situ* moisture observations. The method for incorporating integrated precipitable water observations from GOES and GPS was that described in section 4.

The IPW field at 1200 UTC on this date was above 3 cm through most of the southeastern United States (Fig. 4). A fairly sharp gradient was oriented on a southwest-northeast axis from eastern New Mexico toward northern Missouri. The effect of adding GPS-IPW observations to this field was to add mesoscale detail at scales below those resolvable by the rawinsonde network and below those in the model background field. Areas of relative dryness were made apparent by the GPS observations in northwestern Oklahoma and southeastern Kansas. As a result, a nose of high moisture content in western Missouri became more apparent. This area was the focus for an area of convective precipitation that developed later in the day.

In this case, the result of adding GPS-IPW was to modulate the intensity of the precipitation patterns in the total precipitation forecast between 2100 UTC and 0000 UTC (9-12-h forecast - Fig. 6). These changes were even smaller scale than the analysis changes in the IPW pattern from assimilating GPS observations (Fig. 5). The changes were fairly significant in terms of their actual magnitude (up to over 8 mm more precipitation in the 3-h period in some areas, and almost 6 mm less in other areas. The pattern in Missouri was slightly improved, but the planned investigation over many cases is necessary to make firm conclusions about the influence of GPS-IPW observations on real model forecasts.

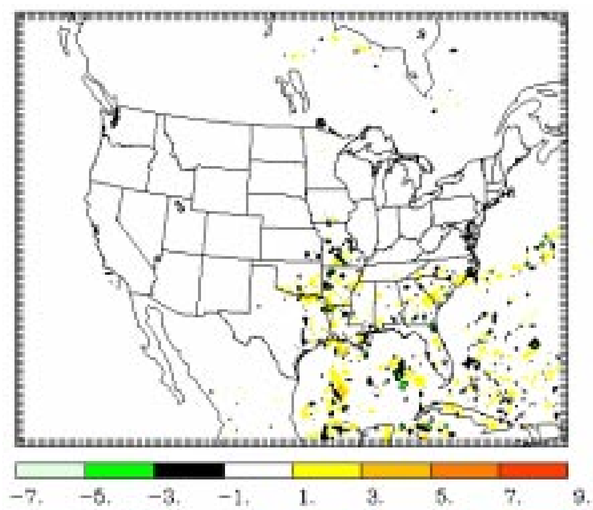

Figure 6. Difference (mm) in 9-12 h precipitation forecasts between RUC-2 model runs with and without GPS-IPW observations. Positive means more precipitation with GPS-IPW.

An interesting feature in the precipitation difference field (Fig. 6) is that there has been a widespread propagation of the effects of GPS-IPW observations through the moist southeast quadrant of the model domain. We believe that this propagation is through changes to convective precipitation in the area of the GPS observations and subsequent gravity wave propagation throughout the model domain. Only in the southeastern quadrant is the atmosphere conditionally unstable, so this is where the initiation of subsequent convection has been changed. Similar features are apparent in the forecast difference field for integrated precipitable water (Fig. 7). Although this effect through gravity waves has not been studied thoroughly, we believe that the model is "touchier" than the real atmosphere in producing such a "long distance" effect.

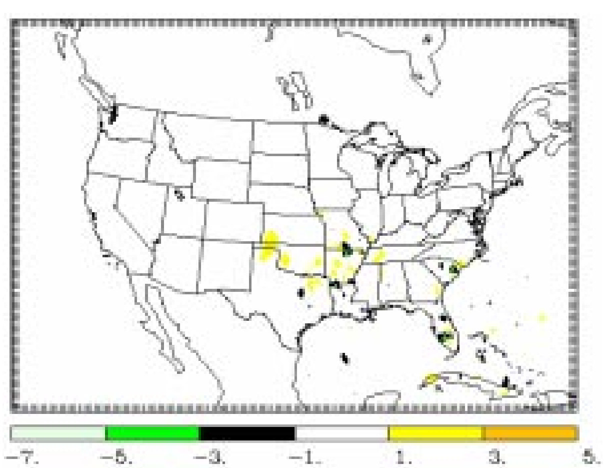

Figure 7. Same as Fig.6, but for 12-h forecast of precipitable water (mm).

6. SUMMARY

Several aspects of use of GPS-IPW observations in operational numerical models have been discussed. GPS-IPW appears to provide an complementary data source to GOES, since it is available in cloudy conditions. The accuracy needed is shown to be 1-1.5 mm. A technique for incorporating GPS (and other) precipitable water observations into RUC-2 was described. An initial case was run with RUC-2 model forecasts with and without GPS observations in which GPS produced some fairly strong local variations in convective precipitation. A planned sensitivity experiment over many cases, but initial considerations indicate that GPS-IPW may be an inexpensive but valuable addition to the composite observing system.

7. ACKNOWLEDGMENTS

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